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REPORT

A reflection modulator for adding data to a composite television signal at u.h.f.

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Summary

A basic reflection modulator cannot be used to add data to a composite television signal at u.h.f. This report describes the modifications which must be made to a reflection modulator so that it can be used for this purpose. Particular attention is given to the addition of narrowband data to lines in the field-blanking interval.

There is a discussion of electronically-variable loads which can be used in this type of modulator. These loads are the pin diode and the field-effect transistor.

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1. Symbols

f_c	critical frequency of pin diode
f_m	modulation frequency
f_{rf}	radio frequency
g_o	conductance of the material in the f.e.t. channel
G_d	conductance of the pin diode
i_d	current flowing in the pin diode
I_n	normalised value of i_d
$I_{0,1,2}$	amplitude of currents flowing in the pin diode at various frequencies
k	constant
L	separation of the source and drain of an f.e.t.
Q_d	stored charge in a pin diode
Q_o	initial value of the stored charge in a pin diode
R_D	channel resistance of an f.e.t.
R_L	load resistance
R_o	characteristic impedance of a lossless transmission line
t	time
V_D	drain voltage of f.e.t.
V_G	gate voltage of f.e.t.
V_i	magnitude of the incoming voltage wave along a transmission line
V_o	characteristic voltage of an f.e.t.
V_r	magnitude of the reflected wave in a transmission line
V_S	source voltage of f.e.t.
ρ	reflection coefficient
τ	minority carrier lifetime in a pin diode
ω	angular frequency

2. Introduction

Some lines in the field-blanking interval are now being used to transmit signals other than picture information. The signals can be either test signals, as in the case of the Insertion Test Signal (ITS), or data as in CEEFAX and the Insertion Communication Equipment (ICE). Some of these use digital techniques (CEEFAX and ICE); some use analogue (ITS).

These signals are added to the picture signal at baseband frequencies. In most cases it is easy and convenient to do this.

In the future we may wish to add data signals at a place where there is no feed of baseband. For example, there is a proposal to add data signals at some u.h.f. relay stations to provide monitoring information. Although it is possible to add the data at baseband by demodulating the u.h.f. signal, this process would be costly.

This report describes a version of reflection modulator which will add data to a composite television signal at u.h.f. There is an emphasis on adding digital information at slow rates to lines in the field-blanking interval. In principle, however, this technique could be used to add faster signals to any other part of the signal.

The theory behind reflection modulators is well known. Some have been commercially available for a few years, but these are for specialist applications and are not suited to use with television signals.

Two problems arise when a reflection modulator is used to modulate a composite television signal. The first is the presence of the two separate carriers, the vision and the sound. Only the vision carrier should be modulated, but any simple reflection modulator will modulate both. The second problem is that a reflection modulator will produce a signal with a double sideband, whereas the television signal is transmitted with a vestigial sideband.

These two problems can be overcome when slow data is added in the field-blanking interval. In this case the modulator can be modified by adding a filter which prevents modulation of the sound. Also, the vestigial sideband presents no difficulties for slow data rates, as will be shown later.

3. Theory of a reflection modulator

The theory of the reflection modulator is based on the fact that a mismatched transmission line will reflect part of any signal travelling along it. Consider a transmission line with a resistive termination at one end. If the line is not matched, then part of any wave incident on the load will be reflected: the remainder will be absorbed by the load. The ratio of the incident and reflected waves, the reflection coefficient, is given by:[1]

$$\frac{V_r}{V_i} = \rho = \frac{R_L - R_o}{R_L + R_o} \tag{1}$$

When the resistance of the load is varied, the reflection coefficient and the amplitude of the reflected wave also vary. The relationship between the resistance and the reflection coefficient is not linear.

The reflection modulator uses this variation in reflection coefficient to modulate a signal. The amplitude of the reflected wave is controlled by an electronically-driven load.

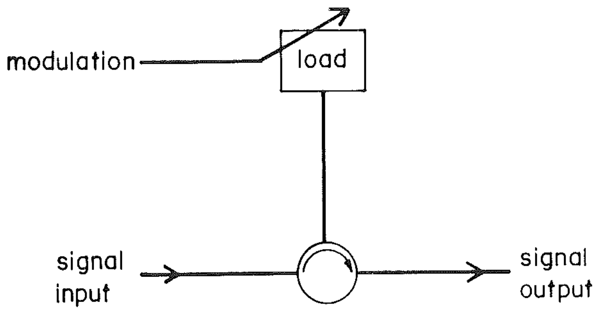

Fig. 1 - A simple reflection modulator

Then the reflected wave is separated from the incident wave by passing it through a circulator as in Fig. 1. In this way, the output becomes a modulated version of the input.

The use of two types of device as a variable load in a reflection modulator is considered. They are pin diodes and field-effect transistors (f.e.t.). Both of these can be used as variable resistances at u.h.f. Their use is described in more detail later in this report.

4. Theoretical problems

There are two problems to be overcome before the basic modulator can be used in a television system. The first arises because we wish to modulate the vision carrier only, but are provided with a composite television signal. The second arises because we must radiate a signal with a spectrum that has a vestigial sideband. The reflection modulator will produce a double sideband.

4.1. Prevention of modulation of the sound carrier

There are two carriers in a television signal. The first is the vision carrier which we wish to modulate during the field-blanking interval. The second is the sound carrier which we wish to leave unaltered.

If the sound carrier accompanies the vision carrier through the reflection modulator, it too will be amplitude modulated. Some of this amplitude modulation will be rejected by the receiver. If the modulation is at too high a level it will not be rejected,[2] and distortion of the sound signal will occur. The amount of distortion will depend on the type and frequency of the modulation.

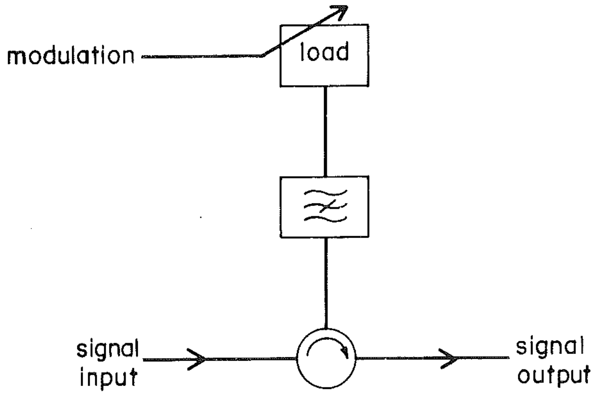

Fig. 2 - A reflection modulator with a filter to reject the sound carrier

The sound carrier can be separated from the vision before modulation to avoid distortion of the sound. This can be done by adding a filter to the basic circuit shown in Fig. 1; the additional filter is shown in Fig. 2. The filter can be either a low-pass, bandpass or bandstop filter. It should allow the vision signal to pass on to the load, but should reflect the sound back to the circulator without being modulated.

If data with a wide bandwidth is added to the vision signal the filter's specification is difficult to meet. If the filter does not have a sharp cut-off, then it may reflect part of some signals and transmit the rest. When the two components are combined later they will have suffered a phase change which may depend on frequency. The resultant will thus have an amplitude which depends on the frequency of the signal, i.e. the picture is impaired. To avoid this the filter must have a high Q, which is expensive at u.h.f.

Fortunately, the problem can be avoided when narrowband information is added during the field-blanking interval only. Suppose the modulator only adds data to lines in the field blanking interval. During the rest of the picture it will act as a perfect reflector, and could be replaced by a short circuit. This short circuit can take the form of a pin diode switch placed just before the filter (Fig. 3). The high-frequency information in the original signal would not have to pass through the filter but would be reflected by the switch. This avoids the distortion caused by a filter which does not have a sharp cut-off. The u.h.f. signal would only be allowed through the filter at times when the modulation is to be impressed on it. If the modulation frequencies are restricted to less than the normal vision bandwidth, then the filter specification is not so critical and can be relaxed.

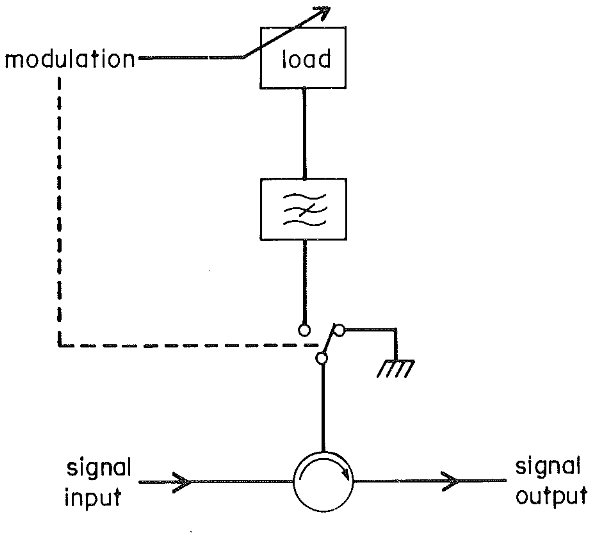

Fig. 3 - A switched version of the reflection modulator

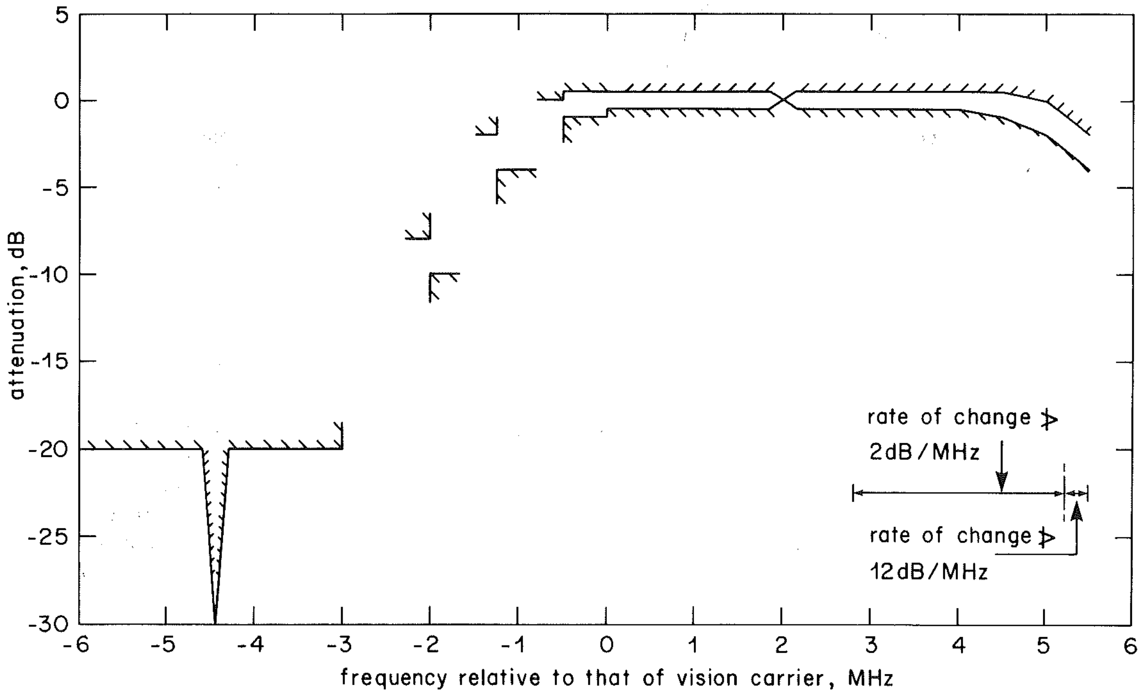

Fig. 4 - The specification of the vestigial sideband

4.2. The vestigial sideband

The second problem that must be considered is the need to preserve a vestigial sideband spectrum. Television signals are radiated with part of their lower sideband attenuated as shown in Fig. 4. The reflection modulator will modulate the carrier giving two sidebands, upper and lower, which will be equal in size.

Care must be taken to ensure that the specification of the vestigial sideband (v.s.b.) is not infringed. There are two ways to do this. One way is to modify the filter to give the correct response. The other way is to restrict the range of frequencies of modulation.

Restricting the range of frequencies of modulation is a simple solution. Signals with a low bandwidth can be transmitted with a full double sideband. Providing the modulation frequency is less than 1·25 MHz they will not infringe the v.s.b. specification (Fig. 4). Unfortunately this means that the full capacity of the channel is not being used.

Another solution is to modify the filter which rejects the sound. This filter can be made so that it shapes the spectrum of the added modulation to conform with the specification. Unfortunately such a filter would be difficult to make in practice.

5. Practical problems

There are two practical problems to be solved before the modulator can be built. First, a suitable filter must be chosen. Then a suitable load must be found.

5.1. The filter

The filter must possess two properties:

(i) Low passband attenuation. If the attenuation is significant the ratio of the amplitudes of the sound and vision carriers will alter. This ratio must be maintained between fairly strict limits.

(ii) The rate of cut-off should be high. The shape of the filter's characteristic depends on its application. In all cases there should be less than 5% amplitude modulation added to the sound carrier. This implies a rejection of the sound carrier of at least 13 dB.

UHF filters with these properties must have a high Q factor. Low attenuation in the passband and high rates of cut-off are difficult to achieve at these frequencies. Any loss in the filter will lead to a degradation in its performance, so losses must be kept low.

Because of this the filter cannot be made out of stripline as the losses in stripline are too great. Useful filters are comb line filters, cavity filters and capacity-coupled half-wavelength resonators.

5.2 The load

The variable load should ideally satisfy four requirements:

(i) It should modulate up to the maximum frequency required. This could be as high as 5·5 MHz, but is more likely to be 1·25 MHz.

(ii) It should give 100% modulation.

(iii) The modulation should be linear. The modulation impressed on the carrier should be proportional to the incoming signal. If this is not the case, some form of correction must be provided, otherwise distortion of the pulse shape will occur.

(iv) It should be able to modulate carriers at moderate power levels.

Unfortunately there is no load which satisfies all these requirements. This is partly because the basic equation relating the load and the reflection coefficient (Equation 1) is non-linear. Other problems affect individual devices.

Two devices satisfy some of the requirements. They are the pin diode and the field-effect transistor (f.e.t.). The pin diode is limited to a low modulation frequency. The f.e.t. has a low depth of modulation in 50Ω systems and is restricted to use with low power signals.

5.2.1. The pin diode

The pin diode can be used as a variable load.[3] It is restricted in use to low modulation frequencies, for reasons which are bound up with the physics of the device.

A simple theory states that the conductance of a pin diode is proportional to the charge stored in its intrinsic region. This charge is related to the current flowing into the device and the rate of recombination of minority carriers. They are related by the law of conservation of charge.

$$G_\mathrm{d} = kQ_\mathrm{d} \tag{2}$$

$$i_\mathrm{d} = \frac{\mathrm{d}Q_\mathrm{d}}{\mathrm{d}t} + \frac{Q_\mathrm{d}}{\tau} \tag{3}$$

The conductance of the diode depends on the low frequency components of its driving current. For example, suppose the current through the diode is made up of three components; a d.c. component, a low frequency component and a high frequency component. The effect of the d.c. and low frequency components on the conductance of the diode is significant, whilst the high frequency component is not. The dividing line occurs at a frequency which depends on the carrier lifetime.

This can be shown mathematically by solving Equation (3) for Q_d

If $$i_\mathrm{d} = I_\mathrm{o} + \sum_{r=1}^{\infty} I_\mathrm{r} \cos \omega_\mathrm{r} t \tag{4}$$

$$Q_\mathrm{d} = Q_\mathrm{o}\mathrm{e}^{-t/\tau} + I_\mathrm{o}\tau + \sum_{r=1}^{\infty} \frac{I_\mathrm{r}\tau \cos(\omega_\mathrm{r} t + \phi_\mathrm{r})}{(1 + \omega_\mathrm{r}^2\tau^2)^{1/2}} \tag{5}$$

The first term is a transient and soon dies away. The second term is due to the direct component of current. The co-sinusoidal terms have a magnitude which is largely independent of frequency when the product $\omega^2\tau^2$ is negligible, i.e. at low frequencies. At high frequencies the magnitude of the terms becomes negligible, tending to zero as the frequency tends to infinity.

The point at which the fluctuation in charge in the diode becomes half the low frequency fluctuation, occurs at a frequency (say the critical frequency) given by

$$f_\mathrm{c} = \frac{1}{2\pi\tau} \tag{6}$$

The maximum frequency of modulation should be less than the critical frequency if a pin diode is used as a load. Above this frequency the variation of conductance becomes significantly dependent on frequency. Preferably the maximum frequency of modulation would be an order of magnitude less than the critical frequency.

The minimum radio frequency should be considerably more than the critical frequency. If this is so, the r.f. signal will have a negligible effect on the conductance of the diode. The load will then appear as a linear resistance to the r.f. signal.

Two problems can arise when a pin diode is used as a load in the modulator. The first is the problem of self biasing. The second is due to a combination of the device's non-linearity and its critical frequency.

The r.f. signal can affect the diode's conductance under certain conditions. When little direct current is applied to the diode, a small amount of rectification of the r.f. signal can occur. In some cases the applied current is less than that obtained from rectification. Because of this it can be difficult to control the resistance accurately when low bias currents are applied. It is best to use high bias currents therefore.

The variation of the reflection coefficient with bias current is highly non-linear. If Equation (3) is simplified to

$$i_\mathrm{d} = \frac{Q_\mathrm{d}}{\tau} \tag{7}$$

and combined with Equation (2) and (1) the result is

$$\rho = \frac{1 - I_\mathrm{n}}{1 + I_\mathrm{n}} \tag{8}$$

where I_n is a normalised value of i_d.

$$I_\mathrm{n} = R_\mathrm{o}k\tau i_\mathrm{d} \tag{9}$$

The variation of ρ with I_n is plotted in Fig. 5. It is highly non-linear, especially for $I_\mathrm{n} > 1$. Below this current there

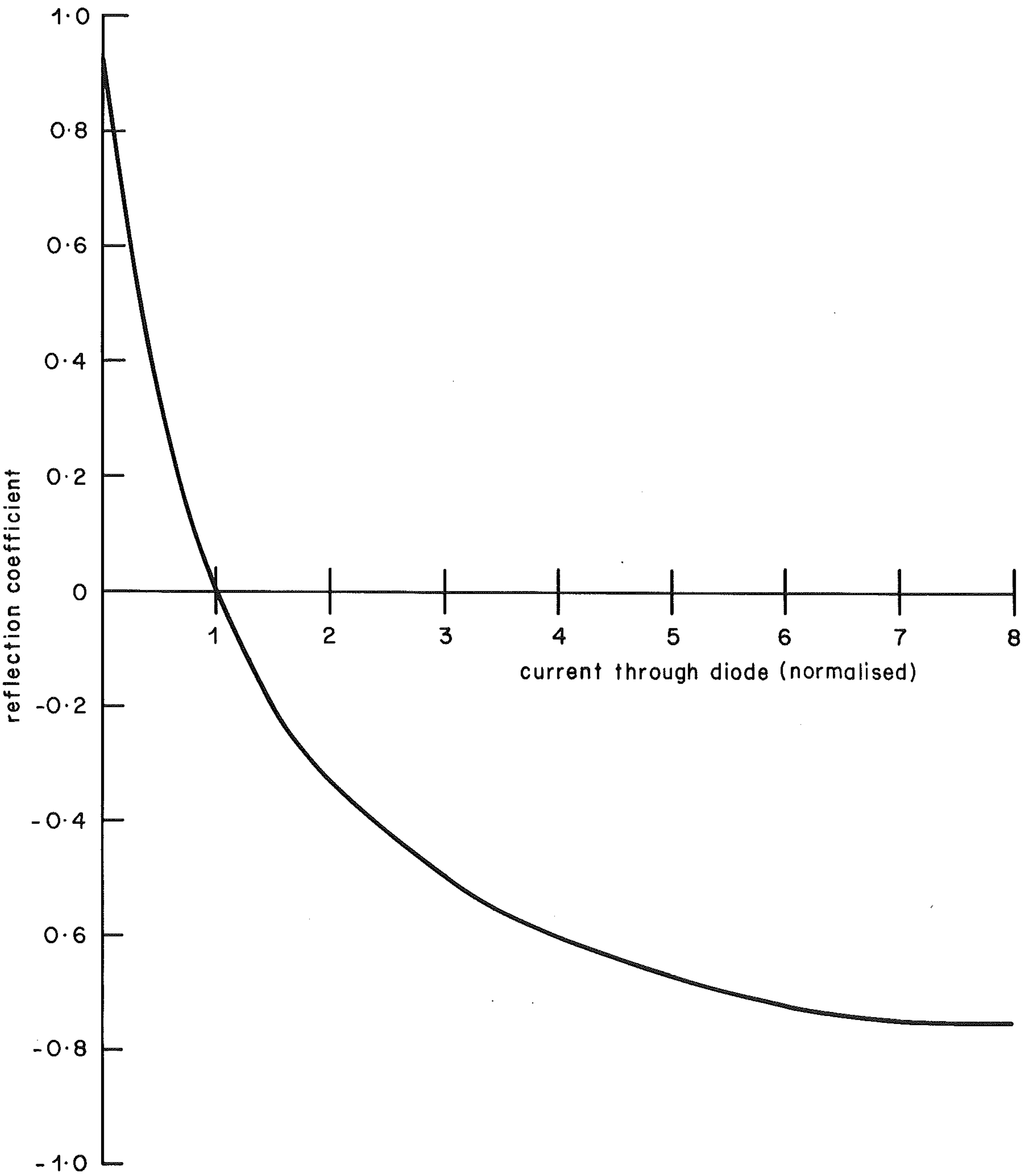

Fig. 5 - Variation of reflection coefficient with current flowing through the pin diode

may be problems with self-biasing. Above this it is non-linear and needs compensation.

The bias current can be corrected for this non-linearity. This can be done by using an amplifier with non-linear feedback (Fig. 6). The amount of correction depends on the operating region of the diode and the degree of accuracy required.

The precorrection will give a bias current which contains harmonics of the original modulating signal. As the pin diode needs a severe non-linearity, the harmonics of the original signal in the bias current will be significant. Harmonics up to the tenth order could be important.

These harmonics must be less than the critical frequency of the diode. Ideally, they would be an order of magnitude below this. If not, the diode's conductance will depend on the frequency of modulation as well as the driving current. This restricts the maximum frequency in the bias current to about $f_c/10$. If this is the tenth harmonic of the modulation frequency and the minimum radio frequency is $10 f_c$ this gives.

$$100 f_m < \frac{1}{2\pi\tau} < \frac{f_{rf}}{10} \tag{10}$$

A typical value of lifetime can be as low as 15 ns. This

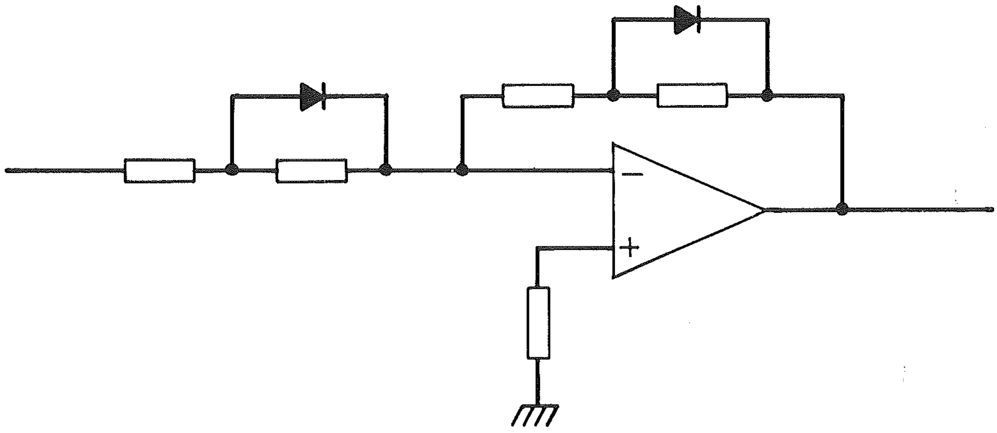

Fig. 6 - A non-linear amplifier

gives a maximum frequency of modulation of 100 kHz, and a minimum radio frequency of 100 MHz.

The pin diode is restricted in use by two factors. Firstly, self-biasing leads to distortion at low bias currents. Secondly, the need for pre-correction restricts the modulation frequency to below 100 kHz for some diodes.

5.2.2. The field-effect transistor

A field-effect transistor may be used as a load for a modulator. The range of control is not as great as for a pin diode, also it handles less power. It can, however, be used up to higher modulation frequencies.

An f.e.t. has a semiconductor channel between source and drain whose resistance can be altered by changing the gate voltage. This change in gate voltage alters the width of the channel by changing the size of the depletion layer on either side of it. The range of resistances which can be obtained by this method is from about 150Ω upwards. The lower resistance is the resistance of the undepleted channel, for which 150Ω seems a typical minimum. As the width is narrowed the resistance increases until, at pinch-off, the channel is almost completely blocked by the depletion layer. After pinch-off it is difficult to control the resistance of the channel. The device is used in a region where pinch-off has not occurred. A typical set of characteristics is shown in Fig. 7.

The device must be operated in the region below pinch-off. Below this voltage the resistance of the channel is variable and controllable. Above it, the resistance varies little. This means that the drain voltage of the f.e.t. must be kept low. In some cases the f.e.t. will work satisfactorily with no drain bias at all.

The signal level of the carrier must be at a low level because of this. The carrier voltage must not be so large that it biases the f.e.t. into the pinch-off region. If the carrier does drive the f.e.t. into the pinch-off region, distortion will occur. This restricts the f.e.t. to use in low power systems: typically, it is difficult to cater for signals of more then one milliwatt.

The minimum channel resistance restricts the depth of modulation. As the minimum resistance is about 150Ω, the maximum depth of modulation is 50% in a 50Ω system. An f.e.t. would give a greater depth of modulation in a system of higher impedance. The best system would have a characteristic impedance equal to the minimum channel resistance, but this is high and would be difficult to achieve in practice. One way round this problem is to use a transformer. This may restrict the bandwidth, but would lead to a greater depth of modulation. Unfortunately, the use of a transformer reduces the maximum power level slightly. This is because the voltage swing at the drain of the f.e.t. is restricted by the pinch-off effect. Then if the impedance of the system is increased and the maximum voltage remains constant, the power level must fall.

The variation in the resistance of the channel with gate voltage is non-linear. A simple solution has been derived by Shockley[4] for a junction f.e.t.

$$R_D = \frac{L}{g_o\left(1 - \left(\dfrac{V_G - V_o}{V_o}\right)^{1/2}\right)} \qquad (11)$$

An f.e.t. therefore needs some pre-correction of its input signal. Without this the modulation would be distorted. The correction can be applied by passing the signal through a non-linear amplifier, as in Fig. 6.

The limitations of an f.e.t. occur at higher frequencies than a pin diode. The modulation is limited by the transit time of carriers across the channel which does not become important until ultra high frequencies in f.e.t.s. High frequencies of modulation are therefore possible.

5.2.3. Comparison of pin diodes and f.e.t.s.

Neither the pin diode nor the f.e.t. is ideally suited for use as a load. Each has its faults. Unfortunately there is no other device which is better.

If a high modulation frequency is wanted, a f.e.t.

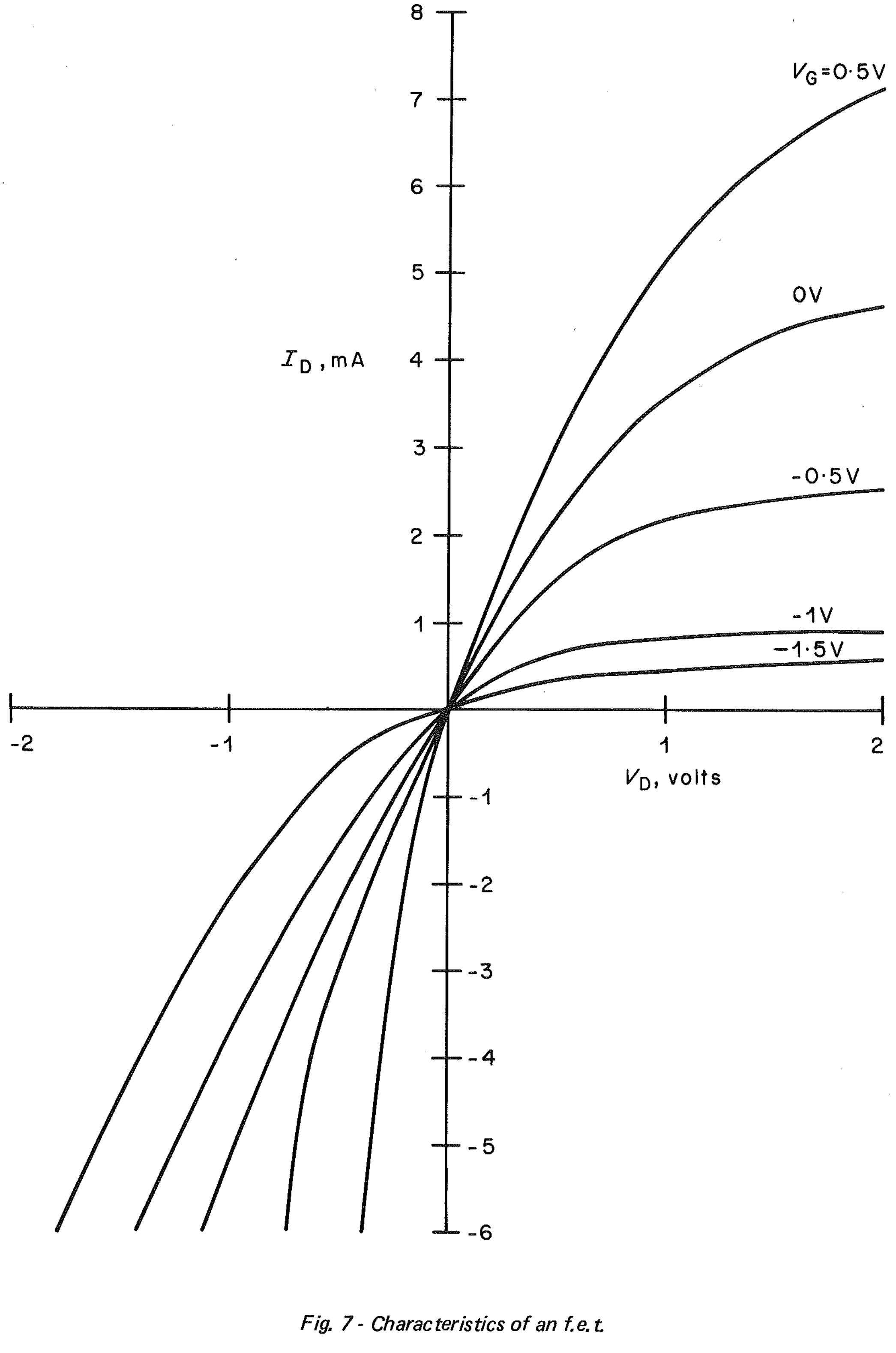

Fig. 7 - Characteristics of an f.e.t.

should be used. This restricts the power level to about 1 mW. With some f.e.t.s. the depth of modulation may be restricted.

If a higher power signal is used, the load should be a pin diode. This will restrict the frequency of modulation to well below the 5·5 MHz needed for video signals.

6. Conclusions

A reflection modulator can modulate the amplitude of a u.h.f. carrier. The basic modulator is not suited for use on u.h.f. television signals, because of the presence of two carriers and the need to preserve the vestigial sideband characteristics.

The basic modulator can be modified for use in television systems by adding a filter and a switch. If modulation of low bandwidth is added during the field-blanking interval, the system is relatively simple to engineer. As the bandwidth of the modulation increases, the specification of the filter becomes more stringent. It may be impractical to manufacture a filter for a large bandwidth model.

Two devices have been examined as possible loads for the modulator. They are the pin diode and the field-effect transistor. Both have limitations in their use. The pin diode cannot modulate signals higher than about 100 kHz, whilst the f.e.t. has a maximum depth of modulation of 50% in 50Ω systems. This can be overcome, but only by reducing the maximum power level through the system.

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